

Effect of in-medium parameters of ρ meson in its photoproduction reactions on nuclei

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Abstract

There exist model calculations showing the modification of the hadronic parameters of ρ meson in the nuclear environment. From these parameters, we extract the ρ meson nucleus optical potential and show the medium effect due to this potential on the ρ meson mass distribution spectra in the photonuclear reaction. The calculated results reproduced reasonably the measured e^+e^- invariant mass, i.e., ρ meson mass, distribution spectra in the $(\gamma, \rho^0 \rightarrow e^+e^-)$ reaction on nuclei.

Keywords: ρ meson photoproduction, ρ meson nucleus interaction, in-medium properties

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1 Introduction

The medium modification of the vector meson is a topic of intense interest in nuclear physics [1]. First indication of the ρ meson modification was seen in the ultra-relativistic heavy ion collision data taken at CERN-SPS [2]. Recent past, STAR experiment at RHIC-BNL [3] found that the decrease in the mass of ρ meson emitted from Au+Au collision is ~ 70 MeV. Contrast to this, the upgraded CERES experiment [4] and the dimuon measurements in NA60 experiment at CERN [5] reported significant broadening (without mass-shift) in the ρ meson mass distribution spectrum.

It is advantageous to search the in-medium properties of vector meson in the normal nucleus over those in the ultra-relativistic heavy-ion collision, since the interpretations of results can be made more judiciously in the previous case where as those in the latter case are very difficult. The model calculations, e.g., scaling hypothesis due to Brown and Rho [6], QCD sum rule due to Hatsuda and Lee [7], vector meson dominance due to Asakawa et al. [8], etc, envisage the reduction of vector meson mass in the nucleus. Boreskov et al., [9] described the broadening of hadronic resonance in the nuclear medium. Using intranuclear cascade (INC) approach, Golubeva et al., [10] studied the medium modification of vector meson in the pion nucleus reaction. In another calculation, Kundu

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et al., [11] showed strong medium effect on the ρ meson in heavy-ion scattering in GeV region. The nuclear medium effect on the vector meson is predicted to be large enough to be observed it in the photon and hadron induced nuclear reactions [12, 13, 14].

Experimentally too, the medium modification of vector meson produced in the lepton and hadron induced nuclear reactions had been reported from various laboratories. The e^+e^- yield in $p+A$ reaction at 12 GeV (measured by KEK-PS E325 collaboration at KEK [15]) is reproduced by the mass reduction of vector meson in the nucleus. The ρ meson production experiment in the $(\gamma, \pi^+\pi^-)$ reaction on the nucleus, done by TAGX collaboration [16], reported the modification of this meson produced in the nucleus. The measurements on the nuclear transparency ratio [17] showed large in-medium width of the ω and ϕ mesons. The in-medium renormalization (i.e., collision broadening) of the ω meson was also seen in the near-threshold photoproduction of this meson [18]. No mass-shift but significant broadening of the ρ meson in the photonuclear reaction has been reported by CLAS collaboration [19]. This meson was probed by its decay product e^+e^- in the momentum range 0.8 to 3.0 GeV/c, and it was produced in the nucleus by 0.61 – 3.82 GeV tagged photon beam at Jefferson Laboratory. The experimental results on this topic, as reported by various collaborations, are tabulated in Ref. [20].

We consider e^+e^- emission in the photonuclear reaction (quoted above [19]) arising due to the elementary reaction in the nucleus: $\gamma N \rightarrow \rho^0 N$; $\rho^0 \rightarrow e^+e^-$. The ρ meson photoproduction is described by the measured reaction amplitude $f_{\gamma N \rightarrow \rho N}$. The modification of this meson occurs due to its interaction with the nucleus. In Ref. [21], we developed this interaction or potential using “ $t\rho$ ” approximation, and used it to calculate the ρ meson mass, i.e., e^+e^- invariant mass, distribution spectra in the $(\gamma, \rho^0 \rightarrow e^+e^-)$ reaction on nuclei. The ρ meson potential can also be extracted from its mass-shift and collision broadening in the nucleus. Using the latter potential, we calculate the ρ meson mass distribution spectra in the above reaction and present them along with the data reported from Jefferson Laboratory [19].

2 Formalism

The differential cross section of the ρ meson mass m distribution in the $(\gamma, \rho^0 \rightarrow e^+e^-)$ reaction on a nucleus [21] can be written as

$$\frac{d\sigma(E_\gamma)}{dm} = \int d\Omega_\rho K_F \Gamma_{\rho^0 \rightarrow e^+e^-}(m) |F(\mathbf{k}_\gamma, \mathbf{k}_\rho)|^2, \quad (1)$$

where K_F denotes the kinematical factor of the reaction: $K_F = \frac{3\pi}{(2\pi)^4} \frac{k_\rho^2 E_{A'} m^2}{E_\gamma |k_\rho E_i - \mathbf{k}_\gamma \cdot \hat{\mathbf{k}}_\rho E_\rho|}$; with $\mathbf{k}_\rho = \mathbf{k}_{e^+} + \mathbf{k}_{e^-}$. E_i is the total energy in the initial state. E_ρ and $E_{A'}$ are the energy of the ρ meson and recoil nucleus respectively. $\Gamma_{\rho^0 \rightarrow e^+e^-}(m)$ stands for the width of the ρ meson

of mass m decaying at rest into dilepton: $\Gamma_{\rho^0 \rightarrow e^+e^-}(m) \simeq 8.8 \times 10^{-6}m$ [22]. $F(\mathbf{k}_\gamma, \mathbf{k}_\rho)$ describes the photoproduction and propagation of the ρ meson in the nucleus, i.e.,

$$F(\mathbf{k}_\gamma, \mathbf{k}_\rho) = \int d\mathbf{r} \Pi_{\gamma A \rightarrow \rho A}(\mathbf{r}) e^{i(\mathbf{k}_\gamma - \mathbf{k}_\rho) \cdot \mathbf{r}} \int_z^\infty dz' D_{\mathbf{k}_\rho}(m; \mathbf{b}, z', z). \quad (2)$$

$D_{\mathbf{k}_\rho}(m; \mathbf{b}, z', z)$ in this equation carries the information about the in-medium properties of ρ meson as it appears in the ρ meson propagator, see below.

The propagation of the ρ meson from its production point \mathbf{r} to its decay point \mathbf{r}' can be expressed as $(-g_{\mu'}^\mu + \frac{1}{m^2} k_\rho^\mu k_{\rho, \mu'}) G_\rho(m; \mathbf{r}' - \mathbf{r})$ [21]. Since the kinetic energy of this meson (of momentum 0.8 to 3.0 GeV/c) is much larger than its potential energy, this meson emits dominantly in the forward direction [21]. We, therefore, represent the scalar part of the in-medium ρ meson propagator $G_\rho(m; \mathbf{r}' - \mathbf{r})$ by the eikonal form, i.e., $G_\rho(m; \mathbf{r}' - \mathbf{r}) = \delta(\mathbf{b}' - \mathbf{b}) \Theta(z' - z) e^{i\mathbf{k}_\rho \cdot (\mathbf{r}' - \mathbf{r})} D_{\mathbf{k}_\rho}(m; \mathbf{b}, z', z)$ [21], where $D_{\mathbf{k}_\rho}(m; \mathbf{b}, z', z)$ is given by

$$D_{\mathbf{k}_\rho}(m; \mathbf{b}, z', z) = -\frac{i}{2k_{\rho\parallel}} \exp \left[\frac{i}{2k_{\rho\parallel}} \int_z^{z'} dz'' \{ \tilde{G}_{0\rho}^{-1}(m) - 2E_\rho V_{O\rho}(\mathbf{b}, z'') \} \right]. \quad (3)$$

$V_{O\rho}(\mathbf{b}, z'')$ is the ρ meson nucleus optical potential which can modify the hadronic parameters of this meson during its passage through the nucleus. $\tilde{G}_{0\rho}(m)$ denotes the free space ρ meson propagator: $\tilde{G}_{0\rho}^{-1}(m) = m^2 - m_\rho^2 + im_\rho \Gamma_\rho(m)$, where m_ρ is the pole mass of this meson. In fact, the above form of the in-medium propagator was used to study the medium effects on the vector meson produced in the nuclear reactions [10, 11].

$\Pi_{\gamma A \rightarrow \rho A}(\mathbf{r})$ in Eq. (2) represents the generalized optical potential or self-energy of the ρ meson which describes its production in the photonuclear reaction [21, 23]:

$$\Pi_{\gamma A \rightarrow \rho A}(\mathbf{r}) = -4\pi E_\rho \left[\frac{1}{\tilde{E}_\rho} + \frac{1}{\tilde{E}_N} \right] \tilde{f}_{\gamma N \rightarrow \rho N}(0) \varrho(\mathbf{r}), \quad (4)$$

where $\varrho(\mathbf{r})$ denotes the spatial density distribution of the nucleus. This distribution is described by two parameter Fermi distribution function for all considered nuclei except ^{12}C , for which it is represented by the harmonic oscillator gaussian distribution [21, 24]. $\tilde{f}_{\gamma N \rightarrow \rho N}(0)$ is the amplitude of the $\gamma N \rightarrow \rho N$ reaction. Its magnitude square, which appears in Eq. (1), can be extracted directly from the measured differential cross section [25]: $\frac{d\sigma}{dt}(\gamma N \rightarrow \rho N)|_{t=0} \simeq \frac{\pi}{k_\gamma^2} |\tilde{f}_{\gamma N \rightarrow \rho N}|^2$. The symbol tilde on the quantities represents those in the ρN c.m. system of energy equal to that in the γN c.m. system.

Eq. (1) can be used to estimate the differential cross section of the $\rho^0(\rightarrow e^+e^-)$ meson mass distribution due to fixed γ beam energy E_γ . But the ρ meson, as mentioned earlier, was produced by the tagged photon beam [19] whose profile (illustrated in Ref. [26]) can be divided into 6 energy bins. Therefore, the cross section can be expressed as

$\frac{d\sigma}{dm} = \sum_{i=1}^6 W(E_{\gamma,i}) \frac{d\sigma(E_{\gamma,i})}{dm}$, where $d\sigma(E_{\gamma,i})/dm$ is given by Eq. (1). $E_{\gamma,i}$ consists of six bins of photon energies, $E_{\gamma,i}$ (GeV) = 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 with relative weights $W(E_{\gamma,i})$ of 13.7%, 23.5%, 19.3%, 20.1%, 12.6% and 10.9% respectively [26].

3 Results and Discussion

The optical potential of the ρ meson can be extracted from its modified mass Δm and width $\Delta\Gamma$ in the nucleus [12]. The latter, i.e., $\Delta\Gamma$, due to its mass modification can be neglected in compare to its collision broadening [13]. The ρ meson optical potential is related to its mass and width [11, 27] as

$$\Delta m(\mathbf{r}) = m^*(\mathbf{r}) - m = \gamma_L \frac{E_\rho}{m} \text{Re} V_{O\rho}(\mathbf{r}); \quad \Delta\Gamma(\mathbf{r}) = \Gamma^*(\mathbf{r}) - \Gamma = -\gamma_L \frac{2E_\rho}{m} \text{Im} V_{O\rho}(\mathbf{r}), \quad (5)$$

where γ_L is the associated Lorentz factor [28]. m and Γ are the mass and width of the ρ meson in free space. The asterisk stands for the in-medium quantities. In fact, these relations are described for the pole mass of the ρ meson. We assume they do not vary with the mass of this meson.

The QCD sum rule calculation due to Hatsuda and Lee [7] have predicted the linear variation of $m^*(\mathbf{r})$ with the nuclear density $\varrho(\mathbf{r})$. According to them, it is

$$m^*(\mathbf{r}) = m[1 - 0.18\varrho(\mathbf{r})/\varrho(0)]. \quad (6)$$

On the other hand, Asakawa et al., [8] in their vector meson dominance (VMD) model calculation have shown that $m^*(\mathbf{r})$ varies non-linearly with $\varrho(\mathbf{r})$, i.e.,

$$m^*(\mathbf{r}) = m/[1 + 0.25\varrho(\mathbf{r})/\varrho(0)]. \quad (7)$$

The in-medium mass m^* of the ρ meson, as shown by Kondratyuk et al. [28], increases with the logarithmic increase in its momentum k_ρ such that (i) $m^* \sim 0.82m$ at the central density of the nucleus as $k_\rho \rightarrow 1$ MeV (see Eq. (6)), and (ii) the mass-shift Δm of this meson is zero at $k_\rho \approx 100$ MeV/c. Effenberger et al., [12] has incorporated such behavior by multiplying the function $f(k_\rho) = \left(1 - \frac{k_\rho}{1 \text{ GeV/c}}\right)$ with the mass-shift (or the real part of optical potential) of the ρ meson. Since this form is linear in k_ρ , it cannot reproduce k_ρ dependence of m^* as described by Kondratyuk et al., [28]. In addition, this form of $f(k_\rho)$ distinctly fails to satisfy the second condition stated above. To overcome these shortcomings, we propose a new form of $f(k_\rho)$ which duly satisfies the behavior of m^* as elucidated above in (i) and (ii):

$$f(k_\rho) = -\frac{1}{2} \left(1 + \log \frac{k_\rho}{k_\rho^0}\right); \quad k_\rho^0 = 1 \text{ GeV/c}. \quad (8)$$

The parametric form of the density dependent ρ meson width $\Gamma_\rho^*(\mathbf{r})$, which is well accord with its dynamically generated width, is given by Weidmann et al. [13] only for $k_\rho \leq 1$ GeV/c. Nothing about it is interpreted beyond this momentum. According to them, $\Gamma_\rho^*(\mathbf{r})$ can be expressed as

$$\Gamma_\rho^*(\mathbf{r}) = \Gamma_\rho[1 + 1.55\varrho(\mathbf{r})/\varrho(0)]. \quad (9)$$

Based on CLAS experimental results reported for $k_\rho = 0.8 - 3.0$ GeV/c, the nuclear density dependence of $\Gamma_\rho^*(\mathbf{r})$ is illustrated by Leupold et al. [1] as

$$\Gamma_\rho^*(\mathbf{r}) = \Gamma_\rho[1 + \varrho(\mathbf{r})/\varrho(0)]. \quad (10)$$

The in-medium width $\Gamma_\rho^*(\mathbf{r})$, as worked out in Ref. [28], weakly varies with the ρ meson momentum.

We extract the ρ meson optical potential from its modified mass and width elucidated in Eqs. (5) - (10), and use them to calculate the ρ meson mass distribution spectra in the $(\gamma, \rho^0 \rightarrow e^+e^-)$ reaction on nuclei for $k_\rho = 0.8 - 3.0$ GeV/c. The calculated spectra due to $ReV_{O\rho}(\mathbf{r})$ evaluated from m^* in Eq. (6) do not differ much from those due to $ReV_{O\rho}(\mathbf{r})$ estimated from m^* in Eq. (7). Hence, we do not present the latter results.

The short-dash curve in Fig. 1 represents the ρ meson mass distribution spectrum for its free propagation, i.e., $V_{O\rho} = (0, 0)$, through ^{56}Fe nucleus. This curve shows that the peak cross section of the considered reaction is $\sim 0.2 \mu\text{b}/\text{GeV}$ which appears at the ρ meson mass equal to 740 MeV. The dot-dot-dash curve refers to above spectrum arising due to the incorporation of the ρ meson optical potential $V_{O\rho}(\Delta m)$, extracted from the mass-shift Δm only (see Eqs. (5) and (6)). It shows the cross section due to this potential is enhanced by a factor of ~ 1.26 at the peak. In this figure, $V_{O\rho}(\Delta m, f(k_\rho))$ illustrates the inclusion of the ρ meson momentum k_ρ dependence in $V_{O\rho}(\Delta m)$ as described in Eq. (8). The dot-dash curve shows that the peak cross section is reduced by a factor of ~ 1.5 because of this potential. $V_{O\rho}(\Delta m, f(k_\rho), \Delta\Gamma)$ represents the ρ meson optical potential extracted from the momentum dependent mass-shift and collision broadening (discussed in Eqs. (5) - (10)). Because of this potential, the calculated cross section (shown by the solid curve) is reduced further by a factor of 1.11 at the peak. This figure also shows that the peak cross section due to the latter potential is reduced by 1.3 in compare to that (short-dash curve) obtained because of the non-interacting ρ meson propagation through the nucleus.

The modification of the ρ meson parameters in the nuclear reaction can occur because of its interaction with the nucleus, i.e., $V_{O\rho}$ in Eq. (5). Therefore, the calculated results with and without this potential can illustrate the medium modification of this meson in the considered reaction, i.e., $(\gamma, \rho^0 \rightarrow e^+e^-)$ reaction on nuclei. The solid and dashed curves in Fig. 2 represent the calculated ρ meson mass distribution spectra with and without

$V_{O\rho}$ respectively. It elucidates the broadening in the ρ meson mass distribution spectrum occurring (more distinctly in heavy nucleus) due to $V_{O\rho}$, without significant peak-shift (within 10 MeV). In Fig. 3, we compare the ρ meson mass distribution spectra calculated for various nuclei. These spectra show insignificant shift of the ρ meson peak-mass but remarkable enhancement in its width with the size of the nucleus.

The calculated ρ meson mass distribution spectrum for ^{12}C nucleus along with the data is shown in the upper part of Fig. 4. Those for ^{48}Ti and ^{56}Fe nuclei (combined) are compared with the data in the lower part of this figure. It shows that the calculated results are accord with the measured distributions reported from Jefferson laboratory [19].

All results, presented so far, are calculated using the imaginary part of the ρ meson potential $ImV_{O\rho}(\mathbf{r})$ extracted from its in-medium width $\Gamma_\rho^*(\mathbf{r})$ given in Eq. (10). To disentangle the effect of $\Gamma_\rho^*(\mathbf{r})$ in Eq. (9) on the ρ meson mass distribution spectrum in the considered reaction, we calculate this spectrum using $\Gamma_\rho^*(\mathbf{r})$ in Eq. (9) for ^{208}Pb nucleus where the medium effect on this meson, as shown in Fig. 2, is the largest. In Fig. 5, this result (short-long-short dash curve) is compared with the previous (solid curve) calculated using $\Gamma_\rho^*(\mathbf{r})$ in Eq. (10). This figure shows that the ρ meson mass distribution spectrum is hardly sensitive to the different forms of $\Gamma_\rho^*(\mathbf{r})$, given in Eqs. (9) and (10).

4 Conclusions

We have calculated the differential cross section for the ρ meson mass distribution in the $(\gamma, \rho^0 \rightarrow e^+e^-)$ reaction on nuclei using the potential extracted from the in-medium parameters of this meson. The calculated spectra show that the broadening (specifically in heavy nucleus) without significant peak-shift occurs because of the ρ meson nucleus interaction. The calculated spectra reproduce the data reasonably. These results corroborate qualitatively those obtained due to the potential evaluated using the ρ meson nucleon scattering parameters [21]. Depending on nucleus, the cross sections in the present case is about 2.5 to 3.5 times larger than those reported earlier in Ref. [21]. Therefore, it is very much necessary to obtain the respective absolute normalized data which can be used to justify the ρ meson potential. Once it is confirmed, the in-medium parameters of ρ meson can be worked out unambiguously.

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Figure Captions

1. (color online). The calculated ρ meson mass distribution spectra due to its potentials extracted from its mass-shift Δm and collision broadening $\Delta\Gamma$ (see text).
2. (color online). Broadening, but essentially negligible peak-shift, in the ρ meson mass distribution spectra occurring due to its potential $V_{O\rho}$. The dashed curve is divided by 1.29 for ^{12}C ; 1.3 for ^{56}Fe and 1.35 for ^{208}Pb .
3. (color online). Enhancement in the ρ meson width with the size of the nucleus. The shift of its mass towards the lower value in the heavier nucleus is insignificant. The short-long-short and dot-dash curves are divided by the factors 3.46 and 4.44 respectively.
4. (color online). The calculated results (solid curve) compared with the data taken from Ref. [19].
5. (color online). The sensitivity of the ρ meson mass distribution spectra to its in-medium widths given in Eqs. (9) and (10). The short-long-short dash curve is obtained because of Eq. (9) for $\Gamma^*(\mathbf{r})$ where as the solid curve arises due to $\Gamma^*(\mathbf{r})$ given in Eq. (10). The previous is multiplied by 1.04.

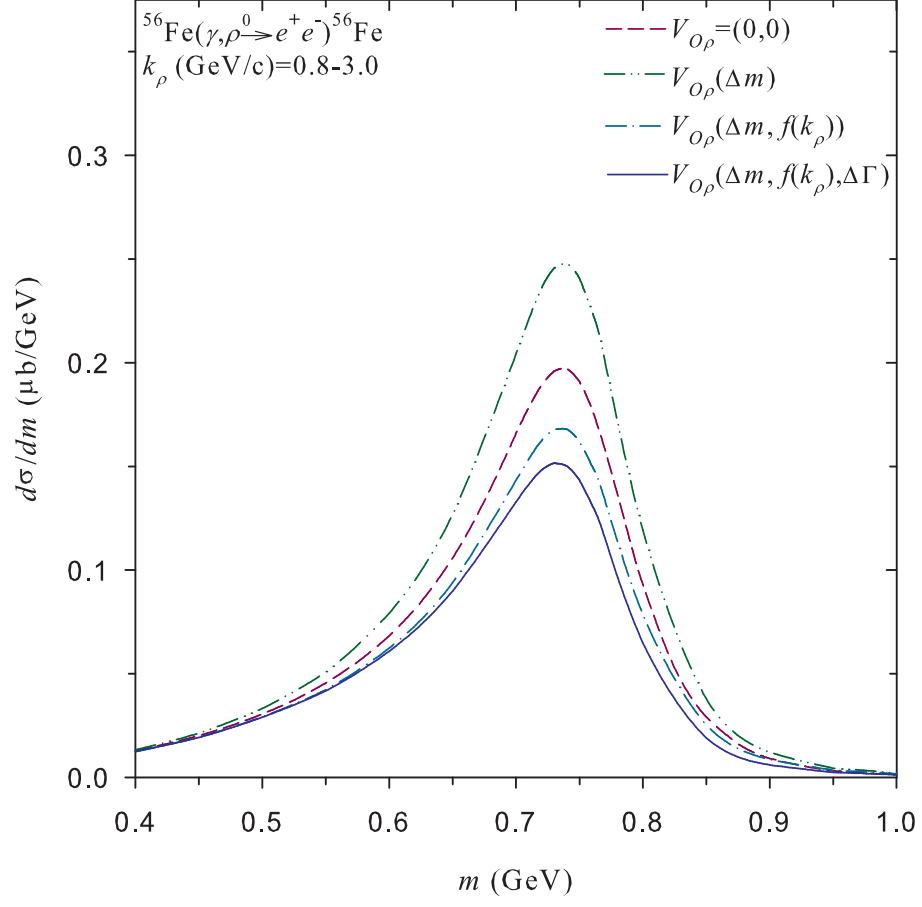


Figure 1: (color online). The calculated ρ meson mass distribution spectra due to its potentials extracted from its mass-shift Δm and collision broadening $\Delta\Gamma$ (see text).

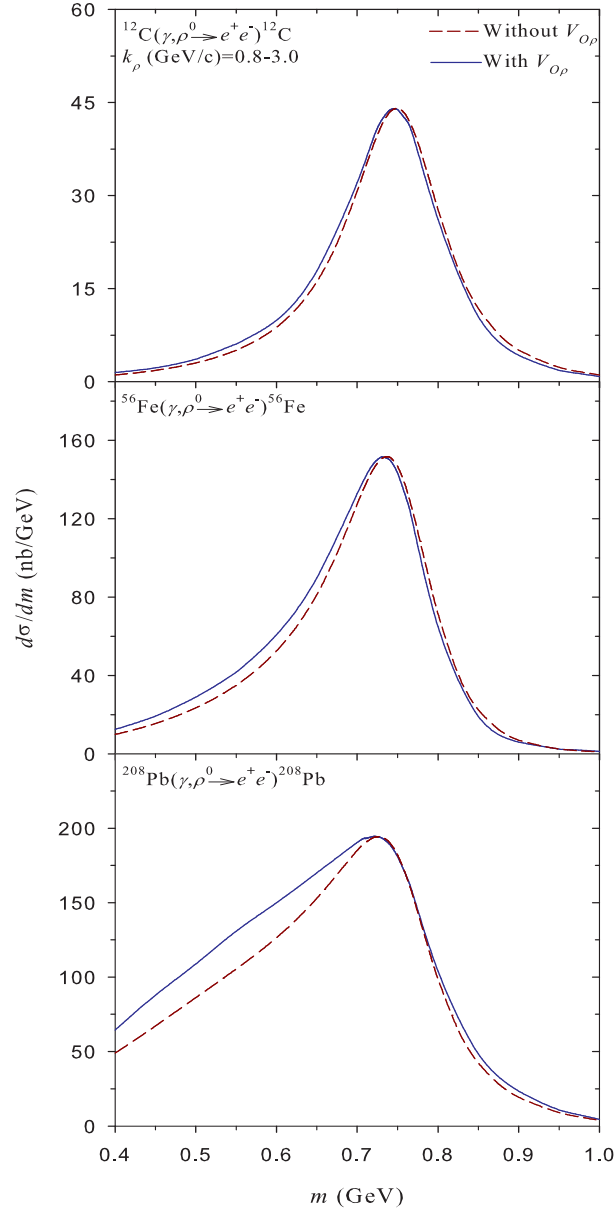


Figure 2: (color online). Broadening, but essentially negligible peak-shift, in the ρ meson mass distribution spectra occurring due to its potential $V_{O\rho}$. The dashed curve is divided by 1.29 for ^{12}C ; 1.3 for ^{56}Fe and 1.35 for ^{208}Pb .

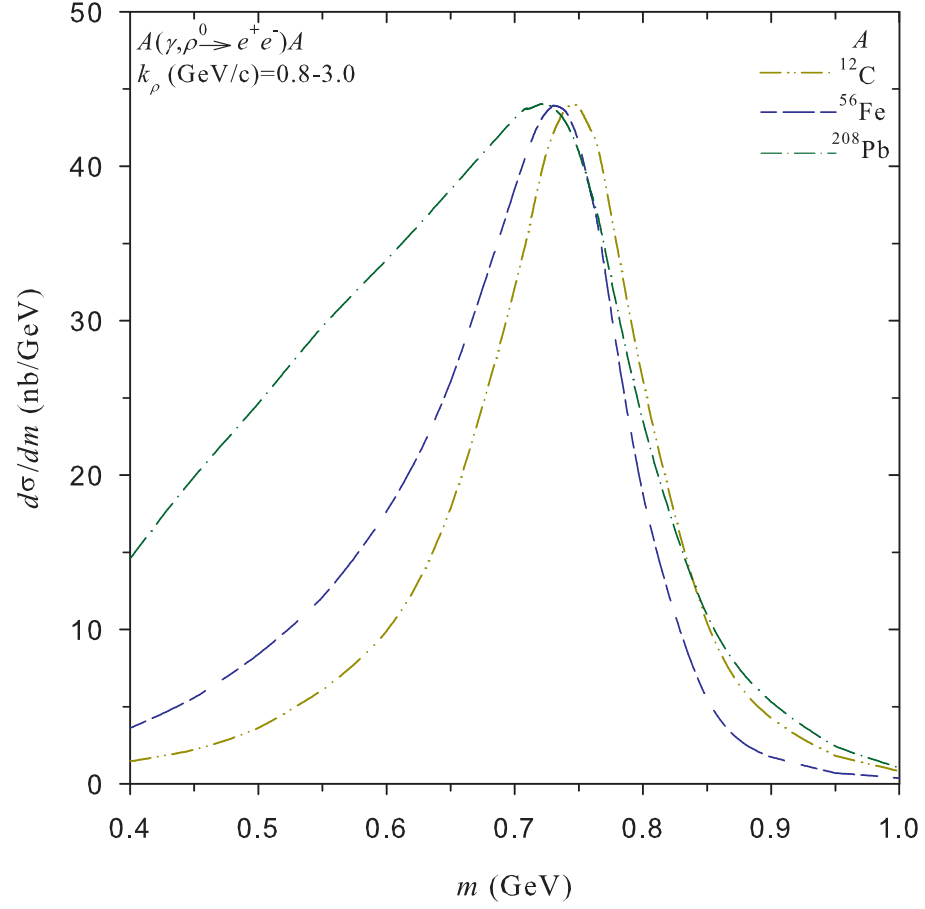


Figure 3: (color online). Enhancement in the ρ meson width with the size of the nucleus. The shift of its mass towards the lower value in the heavier nucleus is insignificant. The short-long-short and dot-dash curves are divided by the factors 3.46 and 4.44 respectively.

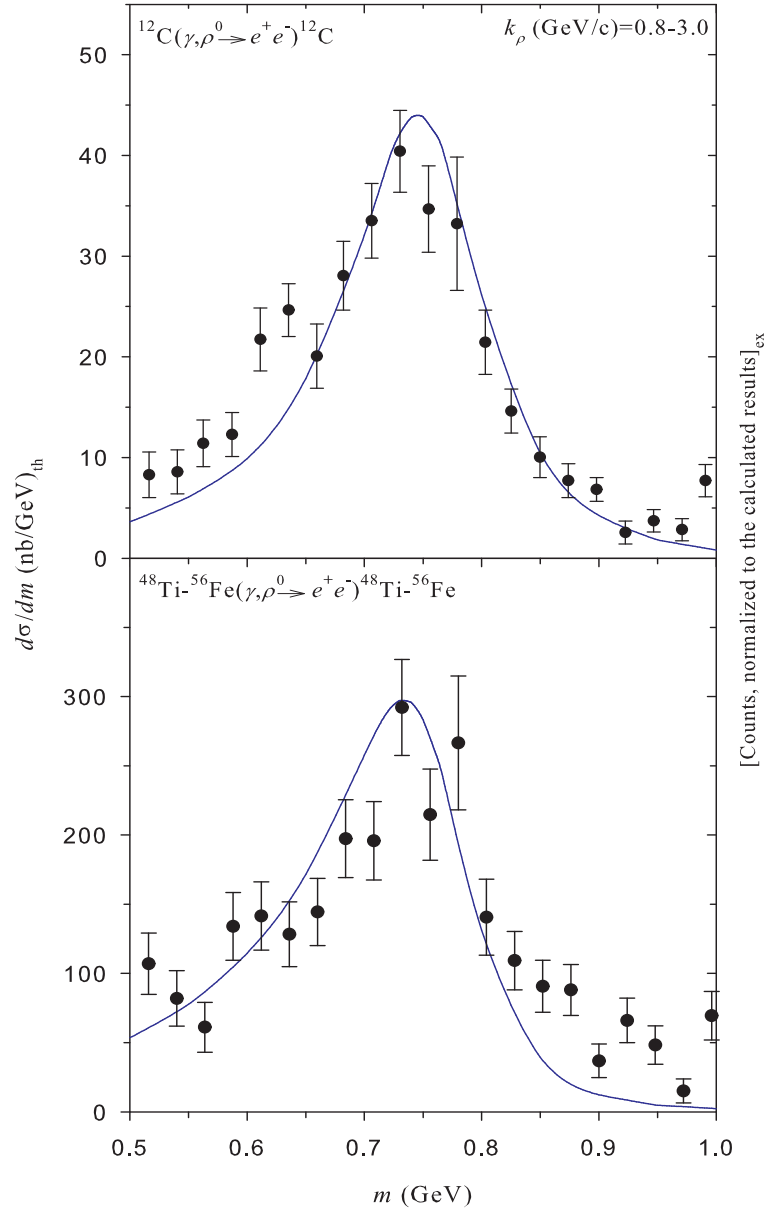


Figure 4: (color online). The calculated results (solid curve) compared with the data taken from Ref. [19].

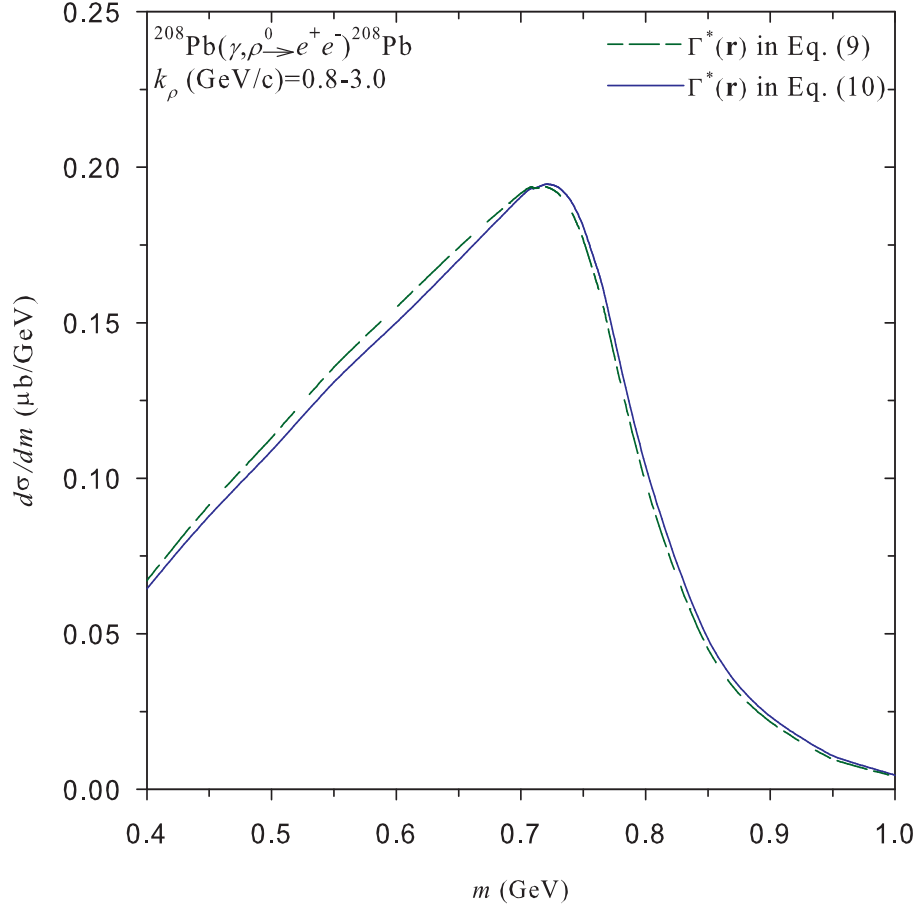


Figure 5: (color online). The sensitivity of the ρ meson mass distribution spectra to its in-medium widths given in Eqs. (9) and (10). The short-long-short dash curve is obtained because of Eq. (9) for $\Gamma^*(\mathbf{r})$ where as the solid curve arises due to $\Gamma^*(\mathbf{r})$ given in Eq. (10). The previous is multiplied by 1.04.